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THICK AND DENSE FOG AT LONDON/HEATHROW AIRPORT AND KINGSWAY/HOLBORN DURING THE TWO DECADES 1950–59 AND 1960–69

By T. KELLY

Introduction. In a previous study,[1] a comparison was made between London/Heathrow Airport, Croydon and Kingsway regarding the occurrence of persistent and semi-persistent thick and dense fog during the period 1947–56. This period was dictated by the closure of Croydon Airport. The study is now brought up to date by considering the fifties and sixties at Heathrow and Kingsway/Holborn* only. As before, 'persistent fog' lasted for 24 hours or more and 'semi-persistent fog' lasted for 12 hours or more, the latter including the former. At Heathrow, a sequence of hourly observations of fog was regarded as being continuous if the visibility rose above the prescribed limits (see below) at single hours only in an otherwise unbroken sequence. (E.g. on 3 October 1953, thick fog was observed at Heathrow at the following times : 00, 01, 03, 04, 05, 06, 07, 09 and 10 GMT. This was considered to be an unbroken period of 11 hours duration.) At Kingsway/Holborn, observations made every three hours (starting at midnight GMT) were used, each observation of fog being assumed to represent a three-hour period of fog. The prescribed limits were such that a visibility of less than 50 metres (55 yards) was defined as dense fog and a visibility of less than 200 metres (220 yards) was defined as thick fog, the latter including the former.

All the basic data were extracted from the original *Daily registers* with the kind permission of the Chief Meteorological Officer, Heathrow, and the Senior Meteorological Officer, London Weather Centre.

Persistent and semi-persistent thick fog. All occasions of semi-persistent thick fog during the 20 years under consideration are listed in Table I.

The detail of Table I is summarized in Table II, which gives the total number and duration of semi-persistent thick fogs during the early and late fifties and sixties.

* The London Weather Centre moved from Kingsway to High Holborn on 9 January 1965.

TABLE I—PERIODS OF SEMI-PERSISTENT THICK FOG 1950–69

		Heathrow P* date/time GMT	E† h	Kingsway/Holborn P date/time GMT	E h
1950	Jan.	26/20–28/01	30		
	Nov.	25/07–25/19	13		
	Nov.	26/07–27/09	27	26/12–27/06	21
1951	Jan.	29/20–30/11	16		
	Oct.	15/22–16/11	14		
	Dec.	13/18–14/11	18	13/21–14/09	15
1952	Dec.	05/16–08/12	69	05/09–05/18	12
	Dec.			06/09–08/09	51
	Dec.	26/22–27/21	24		
1953	Jan.	19/06–20/11	30		
	Mar.	02/21–03/10	14		
	Nov.	17/00–17/12	13		
	Nov.	25/16–26/04	13		
	Dec.	17/22–18/18	21	18/03–18/15	15
	Dec.	20/21–21/09	13		
1954	Nov.	17/22–18/12	15		
	Nov.	19/20–20/09	14		
1955	Jan.	21/16–22/09	18		
	Oct.	11/20–12/11	16		
	Dec.	01/18–02/11	18		
1956	Jan.	04/07–06/11	53	05/06–06/09	30
	Dec.	18/23–19/22	24	19/03–20/03	27
	Dec.	20/01–20/24	24		
1957	Dec.	03/18–05/02	33	04/00–04/09	12
	Dec.	05/07–05/20	14		
1958	Jan.	30/03–31/10	32		
	Oct.	27/20–28/08	13		
	Oct.	28/19–29/08	14		
	Nov.	16/19–17/07	13		
	Nov.	25/00–25/11	12		
	Dec.	03/23–05/01	27		
	Dec.	24/12–25/08	21		
1959	Jan.	13/21–14/16	20	14/00–14/15	18
	Jan.	28/17–30/11	43	29/03–29/24	24
	Feb.	16/22–17/14	17		
	Feb.	17/17–18/12	20		
	Feb.	18/20–19/11	16		
	Nov.	07/00–08/10	35		
	Nov.	12/09–13/01	17		
	Dec.	01/07–02/08	26		
1960	Jan.	06/22–07/11	14		
	Jan.	07/20–08/09	14		
	Jan.	26/01–26/12	12		
	Oct.	17/01–17/12	12		
	Dec.	17/23–18/12	14		
1961	Mar.	09/21–10/08	12		
	Oct.	15/02–15/14	13		
	Dec.	15/00–15/21	22		
1962	Oct.	16/23–17/11	13		
	Dec.	03/18–07/13	92	04/09–06/03	45
	Dec.			06/12–06/24	15
1963	Dec.	26/18–27/11	18	26/21–27/09	15
1964	Nov.	01/20–02/08	13		
1965	Jan.	24/23–25/12	14		
1966	Nov.	24/02–24/22	21		
1967		None			
1968		None			
1969	Dec.	09/01–09/13	13		

* P = period observed. † E = estimated duration.

TABLE II—NUMBER AND DURATION OF SEMI-PERSISTENT THICK FOGS 1950–69

	Heathrow		Kingsway/Holborn	
	Number	Duration *hours*	Number	Duration *hours*
1950–54	16	344	5	114
1955–59	23	526	5	111
1960–64	12	249	3	75
1965–69	3	48	0	0

This table shows that, during the fifties, the incidence of semi-persistent thick fog increased at Heathrow and changed little at Kingsway. At both stations, there was a remarkable decrease during the sixties, the semi-persistent fog 'season' at Heathrow being from 15 October to 10 March. There was one occurrence of persistent thick fog, this being in 1962. Kingsway/Holborn only experienced three semi-persistent thick fogs in the early sixties and two of these were during the period of persistent thick fog at Heathrow. There was none at Kingsway/Holborn during the late sixties.

Persistent and semi-persistent dense fog. All occasions of semi-persistent dense fog are listed in Table III. Here again, there is a spectacular reduction during the sixties and, at both Heathrow and Kingsway/Holborn, the last recorded semi-persistent dense fog during the period under investigation, occurred in December 1962. During the sixties, this was the only occurrence at Kingsway/Holborn and semi-persistent dense fog only occurred three times at Heathrow, all in December. Two of these were during the persistent thick fog of December 1962.

TABLE III—PERIODS OF SEMI-PERSISTENT DENSE FOG 1950–69

	Heathrow			Kingsway/Holborn		
		Period observed date/time GMT	Estimated duration *hours*		Period observed date/time GMT	Estimated duration *hours*
1950	Nov.	26/12–27/04	17	1950	None	
1951		None		1951	None	
1952	Dec.	06/01–07/13	37	1952 Dec.	06/09–08/03	45
1953		None		1953	None	
1954		None		1954	None	
1955		None		1955	None	
1956	Jan.	04/08–05/02	19	1956 Dec.	19/06–19/15	12
	Jan.	05/05–06/03	23			
1957	Dec.	04/15–05/02	12	1957	None	
1958	Nov.	16/19–17/06	12	1958	None	
1959	Feb.	18/20–19/07	12	1959	None	
	Nov.	12/10–13/01	16			
1960		None		1960	None	
1961	Dec.	15/09–15/20	12	1961	None	
1962	Dec.	03/20–05/24	53	1962 Dec.	04/21–05/06	12
	Dec.	06/12–07/06	19			
1963–69		None		1963–69	None	

Thick and dense fog occurrence. In order to see whether, in common with the decrease in semi-persistent fog, there had been a general decrease in the frequency and duration of all thick and dense fog at the two stations, Tables IV, V, VI and VII were produced, giving, month by month, the number of occasions and the total duration of all cases of thick and dense fog. Since single hourly breaks were ignored at Heathrow, it will be appreciated that the totals given for duration of fog in the tables can exceed the actual

number of hours at which fog was reported (e.g. in Table IV, the visibility was 200 metres (220 yards) or more at 40 of the 1968 hours of thick fog in the fifties and 36 of the 1007 hours of thick fog in the sixties).

TABLE IV—NUMBER OF OCCASIONS/TOTAL NUMBER OF HOURS OF THICK FOG AT HEATHROW 1950–69

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Yearly total
1950	7/48	2/8	6/34		2/5	2/9	1/1			3/13	3/43	4/9	30/170
1951	3/25	3/7	3/18			1/1			3/14	9/61	1/5	6/33	29/164
1952	1/7	4/23	3/12			1/3		5/5		5/16	2/15	5/114	26/195
1953	9/74	3/16	10/46	1/8	2/7				4/29	10/48	8/47	9/68	56/343
1954	1/3	3/14			1/3	1/1	1/1	3/12	2/10	1/4	5/32	5/21	23/101
1955	6/41							2/6	1/7	4/38	6/24	4/38	23/154
1956	4/56		1/2		1/4		1/2		2/9	9/54	6/19	6/65	30/211
1957	2/11	3/9	2/10	1/4				1/2	1/3	7/32		7/53	24/124
1958	3/34	2/6	1/2			2/4		1/1	1/6	6/40	9/62	11/94	36/249
1959	4/68	5/62	2/12	1/1					1/2	4/12	4/63	3/37	24/257
Total	40/367	25/145	28/136	3/13	6/19	7/18	3/4	12/26	15/80	58/318	44/310	60/532	301/1968
1960	5/42	3/9	1/2		1/2				3/8	6/21	2/6	7/27	28/117
1961	1/4	5/5	4/24						5/12	7/46	4/18	5/35	31/154
1962	5/14		1/4							9/54	4/10	5/101	24/183
1963	3/21	1/1	2/4	1/1					4/12	1/1	5/28	8/40	25/108
1964	9/50	3/15			2/3	1/4			2/7	5/11	6/33	4/25	32/148
1965	1/14		2/6	3/10					5/15	8/38	2/14	1/4	22/101
1966		1/1	3/10		2/8	1/1		2/3	5/15	2/15	2/29		18/82
1967	1/1	2/7				1/2		1/1	2/5		1/5	3/7	11/28
1968		2/2				2/3				1/4	3/8	1/11	9/28
1969	3/7		2/11		1/5				1/1	6/11		4/23	17/58
Total	28/153	17/50	15/61	4/11	6/18	5/10		3/4	27/75	45/201	29/151	38/273	217/1007

TABLE V—NUMBER OF OCCASIONS/TOTAL NUMBER OF HOURS OF DENSE FOG AT HEATHROW 1950–69

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Yearly total
1950	4/9	1/3	4/15							2/4	4/20	2/3	17/54
1951			1/5						1/7	7/19		3/16	12/47
1952	1/1	2/8	2/6							2/2	2/9	7/62	16/88
1953	4/10	3/5	4/19	1/4					1/3	5/19	2/9	2/9	22/78
1954									1/1		2/4	1/7	4/12
1955	1/1							1/4		2/8	2/7	3/12	9/32
1956	2/42									5/10	4/10	3/7	14/69
1957		1/2	1/2						1/1	3/21		2/20	8/46
1958										2/8	8/30	6/14	16/52
1959	4/23	5/25	1/2							1/1	5/41	4/8	20/100
Total	16/86	12/43	13/49	1/4				1/4	4/12	29/92	29/130	33/158	138/578
1960	3/4	1/4								2/4			6/12
1961			2/16							3/7	1/1	2/18	8/42
1962	1/5		1/2							2/6		6/80	10/93
1963				1/1					1/1		4/12	4/13	10/27
1964	3/10	1/3								1/1		1/2	6/16
1965	1/1			1/1						3/7	1/4		6/13
1966									2/2		2/3		4/5
1967											1/2		1/2
1968										1/1		3/5	4/6
1969	1/1		1/1							1/1		1/2	4/5
Total	9/21	2/7	4/19	2/2					3/3	13/27	9/22	17/120	59/221

In an attempt to show the general trend, Tables VIII and IX were produced, giving the five-year totals for the early and late fifties and sixties. Also included in these tables are the average yearly duration, the average yearly number of occasions of thick and of dense fog and the overall average duration.

Comparison of Table VIII with Table II suggests that, at Heathrow, the late fifties were not particularly notable for the number of occasions of fog formation, with slightly fewer than in the early sixties but once the fog had formed, there was a greater tendency for it to persist than during any of the other five-year periods considered. There was a great reduction in the incidence of both thick and dense fog during the late sixties (Table VIII).

At Kingsway/Holborn, Table IX shows that there, though there were fewer of them, the thick and dense fogs of the early sixties had a slight tendency

to be more persistent than those of the late fifties. Again, the late sixties show a great reduction in both the number and duration of both thick and dense fogs.

TABLE VI—NUMBER OF OCCASIONS/TOTAL NUMBER OF HOURS OF THICK FOG AT KINGSWAY/HOLBORN 1950–69

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Yearly total
1950	1/9		2/12								3/30	1/6	7/57
1951	2/12								1/3	3/18		2/18	8/51
1952			1/6							1/3	2/9	5/81	9/99
1953	2/6	1/3	2/18						2/6	1/6	1/3	4/27	13/69
1954	1/3							1/3			1/3	1/3	4/12
1955	5/15									2/12		1/6	8/33
1956	2/36								2/6	4/15		3/33	11/90
1957										1/6		2/21	3/27
1958	2/12									3/9	3/15		8/36
1959	4/48	4/15	1/3							2/6	3/9	4/18	18/99
Total	19/141	5/18	6/39					1/3	5/15	17/75	13/69	23/213	89/573
1960	4/21			1/3						1/3			6/27
1961			3/12							1/6		1/9	5/27
1962										3/15		3/63	6/78
1963	2/6										2/12	2/18	6/36
1964	2/9				1/3					1/3	3/18	1/3	8/36
1965	1/3									4/18	1/3		6/24
1966	1/3								2/6	1/3			4/12
1967													0
1968												1/3	1/3
1969	1/3		1/3							1/3			3/9
Total	11/45		4/15	1/3	1/3				2/6	12/51	6/33	8/96	45/252

TABLE VII—NUMBER OF OCCASIONS/TOTAL NUMBER OF HOURS OF DENSE FOG AT KINGSWAY/HOLBORN 1950–69

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Yearly total
1950	1/9		1/3								3/18		5/30
1951	1/3									1/3		1/6	3/12
1952											1/6	5/69	6/75
1953			1/3						1/3	1/3		5/15	8/24
1954								1/3					1/3
1955												1/6	1/6
1956	1/6									2/6		2/15	5/27
1957										1/3		1/6	2/9
1958	1/3									1/3	1/3		3/9
1959	2/9											2/12	4/21
Total	6/30		2/6					1/3	1/3	6/18	5/27	17/129	38/216
1960	1/6												1/6
1961													0
1962												3/30	3/30
1963											1/3	1/6	2/9
1964													0
1965	1/3									1/3			2/6
1966													0
1967													0
1968												1/3	1/3
1969													0
Total	2/9									1/3	1/3	5/39	9/54

TABLE VIII—AVERAGE FOG OCCURRENCE AT HEATHROW

	Total duration	Average yearly duration	Number of occasions	Average yearly number	Overall average duration
1950–54	*hours*	*hours*			*hours*
Thick	973	195	164	33	6
Dense	279	56	71	14	4
1955–59					
Thick	995	199	137	27	7
Dense	299	60	67	13	4
1960–64					
Thick	710	142	140	28	5
Dense	190	38	40	8	5
1965–69					
Thick	297	59	77	15	4
Dense	31	6	19	4	2

TABLE IX—AVERAGE FOG OCCURRENCE AT KINGSWAY/HOLBORN

	Total duration	Average yearly duration	Number of occasions	Average yearly number	Overall average duration
1950–54	*hours*	*hours*			*hours*
Thick	288	57	41	8	7
Dense	144	29	23	5	6
1955–59					
Thick	285	57	48	10	6
Dense	72	14	15	3	5
1960–64					
Thick	204	41	31	6	7
Dense	45	9	6	1	7
1965–69					
Thick	48	10	14	3	3
Dense	9	2	3	1	3

The forecasting problem. This can be stated simply, as follows. When will fog form and, having formed, when will it clear? It is not intended here to go into the theory and classification of fog formation but merely to present information which might help forecasters to decide whether, in any given situation, thick or dense fog is climatologically likely to occur in the London area and at Heathrow in particular.

Table X shows all the occasions of thick fog which occurred at Heathrow during the sixties. Using dates as abscissae and times as ordinates, each figure in the table gives the duration of the thick fog which formed at the stated hour. Where thick fog had been recorded already on any given day, subsequent figures are in bold (e.g. on 23 November 1962 fog was observed at 00, 01, 02, 03, 04, 07 and 08 GMT; hence the 2 plotted at 07 GMT is bold). Where there were two or more thick fog formations at the same hour and date in different years, the first occasion is under the correct date and subsequent cases are off-set to the left, with brackets surrounding them (e.g. in three years thick fog formed at 05 GMT on 21 September).

Discussion. As there was such a reduction in the incidence of fog in the sixties, compared with the fifties, only the former will be discussed. Thick fog and dense fog will be treated separately.

(i) *Thick fog.* At Kingsway/Holborn there were only four occurrences of fog during the last three years of the decade. During the whole decade there was no thick fog during the months of February, June, July and August, only one case each in April and May, two in September and three in March. The thick fog season at Kingsway/Holborn is, therefore, October to January and even then, Table VI shows that thick fogs became comparatively rare and short-lived towards the end of the decade. Kingsway/Holborn was free from semi-persistent fogs after December 1962.

A glance at Table X shows that, at Heathrow, thick fog is unlikely to occur in the month of July. There is only a slight chance of it occurring in April, May, June and August and then only for an hour or two near sunrise. The main thick-fog season lasts from September to March, inclusive, and there was roughly four times more fog (formation and duration) at Heathrow than at Kingsway/Holborn. The main thick-fog months are now treated separately.

September. Table IV shows that September was the only month in which the number of thick fogs during the sixties exceeded that during the fifties,

though the total duration was less during the sixties. All the thick fogs were first reported between 01 and 08 GMT. All the thick fogs had cleared by 11 GMT and the majority by 09 GMT.

October. The range of hours over which thick fog was first reported was greater in October than in September. On 15 October 1961, thick fog was first reported at 02 GMT and lasted until 14 GMT. The visibility then fell below the thick fog limit at 17 GMT and, except at 20 GMT, remained below the limit until after midnight. With the exception of this particular case of fog re-formation, thick fogs only formed* between the hours of 20 GMT and 08 GMT and most of them had cleared by 10 GMT. Note that thick fog was *observed* at Heathrow at all hours except 15 and 16 GMT in the sixties.

November. In November, thick fog was observed at all hours of the day and on 24 November 1966 a thick fog, which formed at 02 GMT, lasted until after 22 GMT. On 10 November 1964, there was a thick fog until 06 GMT and the visibility fell below the thick fog limit again at 16 GMT. Apart from this case, thick fog did not form between the hours of 09 and 18 GMT, inclusive. The majority of thick fogs cleared before 09 GMT.

December. On 26/27 December 1963, thick fog was reported from 18 to 11 GMT and formed again at 15 GMT. With this exception, thick fog did not form between 12 and 16 GMT, inclusive, though it was *observed* at all hours. The thick fog which formed at 18 GMT on 3 December 1962 persisted for 92 hours and was the longest persistent fog of the decade.

January. The majority of thick fogs cleared by 11 GMT. On days when thick fog had not been reported previously, the thick fog limit was not reached until 21 GMT but on days when it had been reported previously it re-formed as early as 17 GMT. There were no reports of thick fog between 13 and 16 GMT inclusive.

February. All morning thick fogs cleared before 11 GMT and no thick fogs formed between 10 GMT and 18 GMT, inclusive. Thick fog was not observed at either 00 GMT or 20 GMT. The longest duration was 7 hours from 03 GMT to 09 GMT on 14 February 1961.

March. There was only one period of semi-persistent fog. It lasted for 12 hours, starting at 21 GMT on 9 March 1961, after thick fog in the morning from 02 to 08 GMT. Thick fog was never observed between 12 and 20 GMT, inclusive.

(ii) *Dense fog.* Table VII shows that during the sixties dense fog formed at Kingsway/Holborn only 10 times compared with 38 during the previous decade. None was reported in any of the months from February to September, inclusive. There was one isoiated observation in each of the months of October and November, each giving a nominal duration of three hours of dense fog. Six of the other occurrences were in December and three in January. This small sample suggests that dense fog is not likely to form in central London before midnight or to last much after 09 GMT. After 1962, there were only five dense fogs at Kingsway/Holborn and only one of these (in December

* 'Formed' is sometimes used in this article to mean 'was first reported' or 'was first observed'. Thus fog which 'formed' at 20 GMT might, in fact, have formed at any time after 19 GMT.

TABLE X—THE DURATION IN HOURS OF EACH OCCASION OF THICK FOG WHICH OCCURRED AT HEATHROW DURING THE DECADE 1960–69

September

Time GMT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	Time GMT
00																															00
01																						4	1								01
02																									1				6		02
03																		1						4						6	03
04																										6					04
05																			[4	6	3]	4	[1	6]			5				05
06									1					1																	06
07		1								1				3		3	2						1		1			1			07
08																				1											08
09																															09

October

Time GMT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	Time GMT
16																																16
17															8																	17
18																																18
19																																19
20																						1										20
21																										9						21
22																																22
23									9						13	11																23
00									11						11								1					4				00
01														3		12											1		11			01
02					[4	4	1]				1		[3	13]														6				02
03																				1												03
04		6			2				1													4	1									04
05			1		[4	1]						5	1					1					7									05
06					4	2															5					5						06
07		2												3												2						07
08					1											1					[3	1]										08
09																																09

November

Time GMT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	Time GMT
16										4																					16
17																															17
18																															18
19									6																						19
20	13					3																1	1				10				20
21																		11													21
22																												1			22
23									3																						23
00																								5							00
01						9	1		5	6												5									01
02				8							6													21							02
03																				5							8				03
04									7																	1					04
05										1				1																	05
06																															06
07	2			2																				2							07
08																														3	08
09																															09

December

Time GMT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	Time GMT
15																											8				15
16																																16
17																													1			17
18			9	2							4															18		1				18
19										4																						19
20	1																	4			3											20
21									5																							21
22										10																						22
23		11										2				4	14															23
00						4				2					22		1															00
01	3							13								4								7			1					01
02							1	3																				1				02
03																																03
04																											4					04
05																			7							3						05
06																					2											06
07																																07
08											3																					08
09									1														2									09
10																																10
11	1							2						4																		11

TABLE X—*continued*

January

Time GMT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
16																															
17																					4										
18	2																									1					
19																															
20							14																								
21																			9												
22					[1	14]														3				1							
23			10			5															4		14								
00																							[10	9]			4				
01	5																								12						
02																															
03								4																							
04			1		3																9							2			
05				1							1																				
06																															
07																						3									
08				5																											
09																								2							

February

Time GMT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	27	27	28	29
18																													
19								1																					
20																													
21						3																							
22																		1											
23																									4				
00																													
01						4													6										
02																													
03						2																		5					
04														6														5	
05								6																					
06			1															1											
07																													
08								1												1									
09					2																1								

March

Time GMT	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
20																	
21						12											
22								2									
23																	
00																	
01																	
02						7											
03	6	1															
04	4				6												
05						4											
06						5											
07						1				3						3	
08			4											1			
09																	
10				2													

April

Time GMT	5	8	27	29
20				
21				
22				
23				
00	1			
01				
02				6
03				
04				
05		3		
06				
07			1	
08				
09				
10				

May

Time GMT	3	4	9	13	28	30
02						
03	5					1
04			4	4		
05		2				
06					2	
07						
08						

June

Time GMT	3	14	15	24	30
02					
03					
04			2	4	1
05	2	1			
06					
07					
08					

August

Time GMT	16	17	25
02			
03			1
04			
05		2	
06			
07	1		
08			

1963) extended over more than one consecutive three-hourly observation. Thus, dense fog, like semi-persistent thick fog, is now a rare phenomenon at Kingsway/Holborn.

At Heathrow, the reduction in the number and duration of dense fogs from the fifties to the sixties was not as spectacular as that at Kingsway/Holborn. Table V shows that the number and duration of dense fogs were each reduced by about 60 per cent in the second decade. Most of the dense fogs occurred during October, November, December and January. There were also a few dense fogs in February, March, April and September, the most serious being in 1961 when dense fog was observed from 02 to 07 GMT on 9 March and re-formed at 22 GMT and lasted until 05 GMT on 10 March with another observation at 07 GMT.

Singularities. As can be seen from Table X, during the sixties the greatest number of years in which thick fog formed at Heathrow on the same date in different years was four. These dates were 21 and 24 September, 22 October, 9 November and 9 March. During the fifties, the dates on which thick fog formed during four or more years on the same date were different. There were six years in which thick fog formed on 15 October and five years in which it formed on 12 October during the fifties. There is, therefore, little evidence of any singularities on particular days, though a glance at Table X suggests the possibility that some periods — especially during January and February — have been more favourable to thick fog than others, i.e. there was little or no fog between 9 January and 18 January, 30 January and 3 February, 9 February and 13 February, etc.

Effects of smoke control. The decrease in occurrence of fog in the London area has been attributed to the introduction of smoke control. Brazell[2] gives details of the number of hours of fog at Kingsway, Heathrow, Kew and Croydon for the years 1947 to 1962, inclusive, and discusses the effect of smoke control. The reduction in dense fog (see Table IX) at Kingsway during the late fifties, compared with the early fifties, suggests that the scourge of smog was being defeated already by smoke control in central London. As smoke control areas were extended, this improvement continued and, by the early sixties, the incidence of thick fog was being reduced. This trend continued during the late sixties.

At Heathrow, situated in an area where smoke control was not applied extensively until the early sixties, the improvement in the early sixties was only marginal. There was, however, a significant improvement during the the late sixties, suggesting a direct relationship between the extension of smoke control areas and the reduction in the number of formations and the duration of both thick and dense fog. Not only has the number and total duration been reduced but the average of the duration of the individual periods of fog has also been reduced (see Table IX).

Conclusion. At Kingsway/Holborn, dense fog is unlikely to occur at any time of year. Thick fog occurs most often between October and January, inclusive, but, once formed, will only last for an hour or two.

At Heathrow, the formation of both thick and dense fog is possible. Dense fog is not likely to occur during May, June, July or August and there is only

a very slight chance of it occurring in April, the main dense-fog season being between October and January, inclusive. Thick fog is not likely in July but there is a slight chance of it occurring during April, May, June and August. The main thick-fog season is from September to March, inclusive.

If, as seems likely, the introduction of smoke control areas has been a major factor affecting the reduction in the frequency and opacity of fog at Heathrow, then, even during the winter half of the year, thick or dense fog will only last for a few hours, though there is still a slight chance that thick fog will be semi-persistent during November, December and January.

Acknowledgements. I wish to thank Mr J. Mearns for his invaluable help in assembling, calculating and checking the data used and also for the large amount of typing in which he has been involved. My thanks are also due to Mr I. Jenkins of London Weather Centre and Mr J. Richardson of Heathrow for their confirmation of monthly totals and help in answering queries regarding doubtful observations.

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1. KELLY, T.; A study of persistent and semi-persistent thick and dense fog in the London area during the decade 1947–56. *Met. Mag, London*, **92**, 1963, pp. 177–183.
2. BRAZELL, J. H.; Frequency of dense and thick fog in central London as compared with frequency in outer London. *Met Mag, London*, **93**, 1964, pp. 129–135.

Author's note. Since the completion of the above article, the following data have been received from Messrs Jenkins and Richardson at London Weather Centre and Heathrow respectively, giving the observations of thick and dense fog — hourly at Heathrow and 3-hourly at Holborn — during 1970.

		Thick		Dense	
		Period observed date/time GMT	Estimated duration	Period observed date/time GMT	Estimated duration
			hours		*hours*
Holborn	Jan.	28/03–28/06	6	28/03–28/06	6
	May	09/06	3		
	Nov.	27/03	3		
Heathrow	Jan.	22/21	1		
		25/21–25/23	3		
		27/04	1		
		27/22–28/09	12	27/22–28/09	12
	Apr.	09/04–09/05	2		
	May	14/05–14/06	2		
	Sept.	28/05–28/06	2		
	Oct.	08/04–08/09	6	08/04	1
		12/06	1		
		18/07–18/08	2		
	Nov.	27/01	1		
	Dec.	13/05–13/07	3		
		13/09–13/12	4		
		13/15	1		
		14/09–14/13	5		

These observations are consistent with the conclusions of the foregoing article. The only notable event was the semi-persistent dense fog at Heathrow on 27/28 January, this being the first such occurrence since December 1962.

551.510:551.513.1:523.4

MOTIONS IN PLANETARY ATMOSPHERES: A REVIEW

By R. HIDE, F.R.S.

Introduction. The study of planetary atmospheres is concerned with their origin and evolution, the chemical composition of their main gaseous components, the nature and distribution of large particles in suspension, the mean temperature and pressure of the lower boundary and the nature of that boundary, the nature of small-scale turbulent motions, the nature of energy sources and the nature of large-scale organized motions. Each of these topics is closely linked with most of the others, and any subdivision of the subject of planetary atmospheres into separate areas is inevitably somewhat artificial. Nevertheless, it is of interest in connection with the interpretation of cloud photographs — such as those now being acquired by the International Planetary Patrol[1] — to discuss large-scale organized motions.

Hydrostatic equilibrium. Stable hydrostatic equilibrium of a fluid in a steady gravitational field is possible when

$$\nabla_H \rho = 0 \qquad \ldots (1)$$

and

$$\frac{\partial \rho}{\partial z} - \left(\frac{\partial \rho}{\partial z}\right)_{ad} < \Gamma_{crit}, \qquad \ldots (2)$$

where ρ denotes density, $\nabla_H \rho$ is the horizontal density gradient, $\partial\rho/\partial z$ is the (upward) vertical density gradient, $(\partial\rho/\partial z)_{ad}$ is the adiabatic density gradient.[2] Γ_{crit} represents effects due to damping caused by radiation, viscosity, thermal conductivity, etc.[3] and does not differ significantly from zero in the problems discussed below. The nature of the hydrodynamical flow that occurs when equation (1) and/or equation (2) are not satisfied depends on a wide variety of parameters, and the investigation of such flows constitutes a major part of the subject of 'geophysical fluid dynamics'.[3,4] Hydrodynamical flow occurs in planetary atmospheres because heat sources are present, so that the rather special conditions required for stable hydrostatic equilibrium cannot be met.

Heat sources. It is generally supposed that solar radiation is largely responsible for motions in the atmospheres of Venus, Earth and Mars. Define a dimensionless parameter

$$\tau = \overline{T}/\Delta T, \qquad \ldots (3)$$

where $\overline{T}$ is the mean temperature of the atmosphere and ΔT is the drop in $\overline{T}$ that would occur during one period of rotation if the heat source were suddenly cut off. When $\tau \ll 1$, as in the case of Mars,[5,6] the atmosphere has such a small thermal capacity that it is able to respond everywhere — even at the lowest levels (where the density is highest) — to the diurnal cycle of heating and cooling, so that a 'thermal tide' is a major feature of large-scale motions at all levels. When, on the other hand, $\tau \gg 1$, as in the case of Venus and Earth, the diurnal cycle of heating and cooling has little effect on large-scale motions in the bulk of the atmosphere, although strong thermal tides would occur at very high levels, where the density is low, if solar radiation is absorbed there, and may account for the 100-hour circulation of Venus inferred from ultra-violet observations[7] and for the so-called 'super-rotation'

of the Earth's high atmosphere.[8] The parameter τ has little relevance for the atmospheres of the giant planets if, as now seems likely, internal heat sources are more important than solar radiation.

Rotational effects. The angular speed of rotation, Ω, of a planet enters the two dimensionless parameters :

$$R = U/L\Omega, \qquad \ldots (4)$$

a Rossby number[4] and

$$M = L\Omega/c, \qquad \ldots (5)$$

a 'rotational Mach number.'[9,10] Here L is a characteristic horizontal dimension which, for large-scale motions, can be set approximately equal to the radius of the planet, U is a typical horizontal 'wind' speed relative to the rotating planet, and c is the speed of sound in the atmosphere. For all the planets $RM < 1$ (i.e. wind speeds are typically subsonic). For Venus $R \gg 1$ (and $M \ll 1$), so that dynamical effects due to rotation are small, while for Earth, Mars, Jupiter and the other giant planets (Saturn, Uranus and Neptune) $R \ll 1$ and rotational effects predominate. In the case of Earth and Mars, because M is not much greater than unity the shortest time scales associated with large-scale horizontal motions are typically not much greater than a few 'days' (1 day $= 2\pi/\Omega$ seconds), but in the case of the giant planets, for which $M \gg 1$, these time scales should be very much greater,[9,10,11] which accords with observations.[9]

Vertical stability. The vertical gradient of 'potential density', equal to the left-hand side of equation (2), is also of dynamical importance. When, as in the case of the Earth's atmosphere, this gradient is negative on average, the atmosphere is 'vertically stable', large-scale motions then being a consequence of equation (1) not being satisfied. The determination of the vertical stability of an atmosphere from first principles is a central theoretical problem, and it is now recognized that theoretical models that take into account heat transport by radiation and small-scale turbulence but neglect heat transport by the large-scale organized motions are inadequate.[12,13]

Venus, Earth and Mars.

Venus. The observation that the visible disc of Venus is covered with cloud implies that descending motions are probably restricted to localized regions. The most striking feature of thermal convection in a fluid heated non-uniformly from above is the organization of the descending motions into very narrow regions, with rising motions elsewhere,[14] and this result has been invoked to explain the cloud cover on Venus [15–18] and used as a basis for theoretical models of the deep circulation of Venus's atmosphere.[15,17,18] (See Plate I).

Some observers interpret the apparent motion of faint markings seen in the ultra-violet as evidence of a retrograde circulation of Venus's upper atmosphere with a period of about 100 hours.[7,19] The reality of this circulation is still in dispute, and it is important to investigate this matter further observationally. Theoretical work[13,20] on the nature of the circulation, if it exists, stems from a suggestion by Schubert and Whitehead[21] that the circulation is the rectified motion, due to non-linear effects, associated with the thermal tide in the tenuous outer atmosphere of Venus. (See also Reference 59.)

Earth. A great deal is known from direct measurements about the global circulation of the Earth's atmosphere, especially the lowest few kilometres — the troposphere — which contains most of the mass.[22] The *raison d'être* of the

circulation is the convective transfer of heat from equatorial to polar regions; if the atmosphere did not circulate, differential solar heating would maintain the temperature contrast between pole and equator at several times the observed value. The Earth's rotation, as measured by the inverse of the Rossby number defined by equation (4), inhibits overturning motions in middle and high latitudes and thus constrains the flow to take the form of quasi-horizontal waves ('baroclinic waves' or 'sloping convection'[4,22]). Frontal systems and jet streams — so important in weather forecasting — are necessary concomitants of baroclinic waves, whose sharpening action is eventually regulated by the onset of small-scale instabilities,[23] which are often encountered as clear-air turbulence.

Mars. Observations bearing on motions in the Martian atmosphere are not easy to make and interpret and it will be important, therefore, to exploit theoretical models to the full. The most recent theoretical work is that of Leovy and Mintz,[6] who used the Mintz-Arakawa two-level model for integrating the primitive equations of fluid dynamics, thermodynamics and heat transfer on a high-speed electronic computer. Heating and cooling by solar and infra-red radiation were included, as were effects due to turbulent convection, although effects due to topography (which are probably quite important) were not taken fully into account.

Carbon dioxide is the main atmospheric constituent, and this was allowed to condense on the planet's surface, releasing latent heat where the surface cools to the frost-point. Two numerical experiments were performed, one for the southern Martian summer and the other for the southern autumn equinox. The solstice experiment gave strong zonal mean westerly (i.e. from the west) winds of up to 80 m/s in middle and high latitudes of the winter hemisphere (produced by the net eastward Coriolis torque that accompanied the poleward mass transfer of the condensing CO_2 polar ice-cap), baroclinic waves[4,17] in the winter hemisphere, a strong, thermally direct (i.e. hot fluid rising and cold fluid sinking) mean meridional circulation across the equator, with a strong east–west maximum near the equator and weak easterly winds over most of the southern hemisphere. The results for the equinox experiment are more like conditions in the Earth's atmosphere. In both hemispheres there are zonal mean westerly winds in the mid-latitudes with baroclinic waves in the middle and higher latitudes and easterly winds in the tropics. Large diurnal variations were found in both experiments.

Giant planets. Recent studies of motions in the atmosphere and interior of the planet Jupiter and the origin of his magnetic field include attempts to understand, in terms of hydrodynamical processes, ground-based observations of (i) the Great Red Spot and other less-persistent and generally smaller markings on Jupiter's visible surface,[10,11,24-33] (ii) the banded appearance of the visible surface[34-37] and the complicated and striking variation of rotation rate with latitude, including the pronounced equatorial jet,[24,38-41] and (iii) radio emission on decimetre and decametre wavelengths, especially the characteristic rotation periods of radio sources,[42-44] indicating the kind of theoretical advances[9,11,24,26,45-48] that should follow the acquisition of *(a)* better and more frequent photographs of the giant planets, *(b)* direct measurements of the strength and patterns of their magnetic fields, and *(c)* information about the electrical properties of their lower atmospheres and interiors. (See Plates II – IV).

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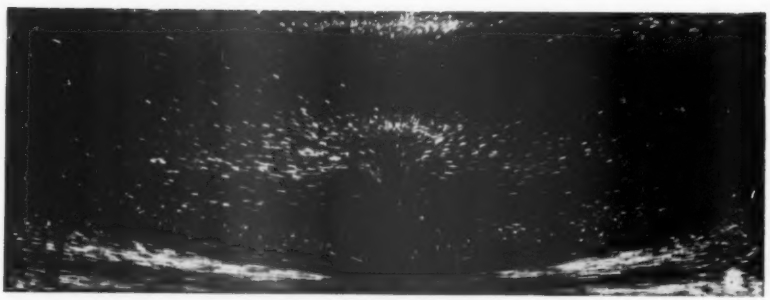
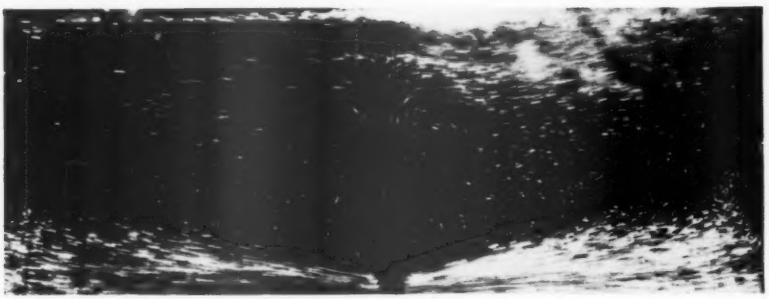


(a)



(b)

PLATE I—STREAK PHOTOGRAPHS ILLUSTRATING THE STREAMLINES OF FLOW CAUSED BY DIFFERENTIAL HEATING OF THE LOWER BOUNDING SURFACE OF A NON-ROTATING FLUID

The middle half of this surface was heated and the remaining parts of the surface were cooled in a symmetrical fashion about the vertical plane through the middle of the apparatus. The other five plane bounding surfaces of the fluid were thermally insulated. The heating rate in case *(a)* was less than in case *(b)*. Note the tendency for the rising motion to occur in a narrow jet and for the horizontal flow near the bottom surface to occur in a thermal boundary layer.[14]

Theoretical models of the deep circulation of the atmosphere of Venus [15–18] stem from the theoretical considerations that led to the above experiments. When the heating and cooling take place at the upper surface, rather than the lower surface it is the descending motion that organizes itself into a jet and an ascending motion occurs throughout the remainder of the fluid. This type of circulation could account for the observation that Venus is almost completely covered with cloud.

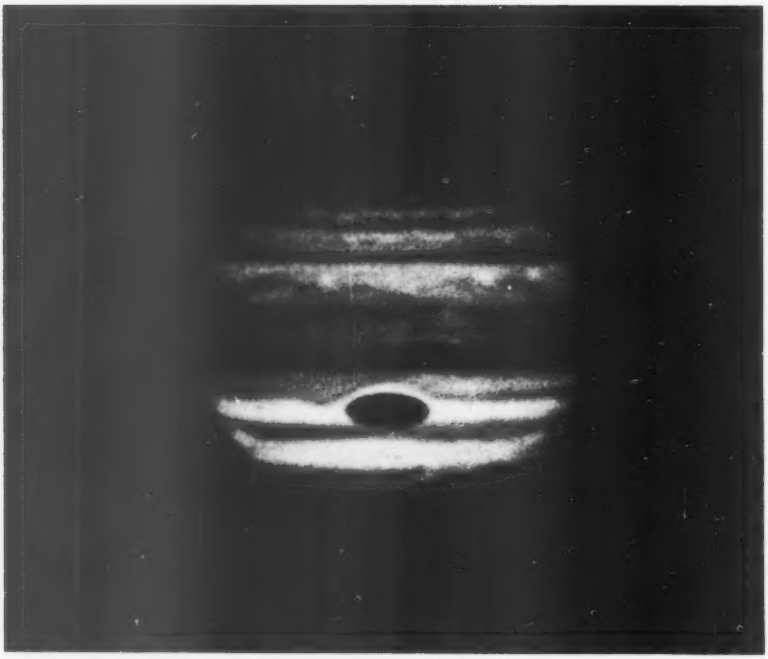


PLATE II—PHOTOGRAPH OF THE PLANET JUPITER TAKEN ON 23 OCTOBER 1964 AT 0905 UT

(Blue light, longitude 255° System 1, 21° System 2)

The Great Red Spot is a prominent feature of the southern hemisphere.

The discovery that the planet Jupiter rotates on its axis with a period of just under 10 hours was made in A.D. 1664, with the aid of one of the first telescopes capable of resolving markings on Jupiter's visible disc of dense ammonia clouds. Subsequent observations revealed that the rotation period of markings within a sharply bounded equatorial zone extending from about 10°S to 10°N is some 5 minutes less than the corresponding period for higher latitude regions of the visible disc (see Plate III). Various lines of evidence indicate that a roughly comparable equatorial current is present at high levels in the atmosphere of the planet Saturn.

Reproduced by courtesy of New Mexico State University

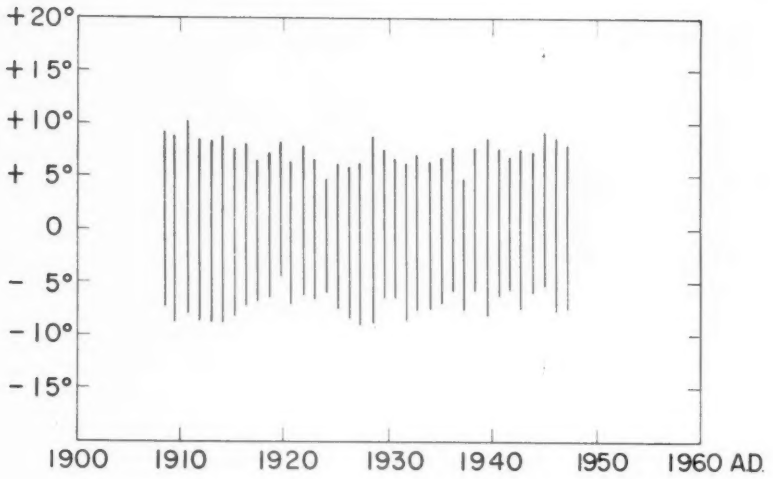


PLATE III—ILLUSTRATING APPARENT VARIATIONS IN WIDTH OF THE EQUATORIAL CURRENT OF JUPITER FROM 1907 TO 1947

Each line indicates the range of latitude occupied by the current (based on a table by Peek[49]).

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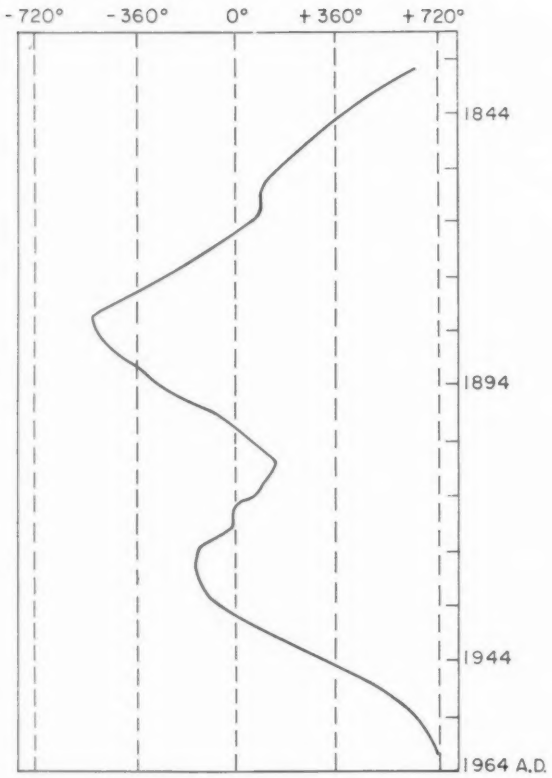

PLATE IV—WANDERINGS OF THE GREAT RED SPOT IN LONGITUDE, 1831 TO 1960

The abscissa is $\lambda_2 - 264{\cdot}3^\circ + 28{\cdot}62^\circ t$ where λ_2 is longitude in System 2 and t is measured in units of 399·88 days, the mean intervals between oppositions of Jupiter. The ordinate is time in years. (After Peek.[49])

According to Hide these wanderings could be a manifestation of variations in the rotation period of the underlying planet.[11,24]

Plates III and IV are reproduced by courtesy of B. M. Peek and Faber and Faber Ltd.

These studies have led to information about the deep interior of Jupiter *that may be obtainable in no other way.*[9,24,45,48,55] Horizontal and vertical transfer of angular momentum within Jupiter are implied by the existence of the equatorial jet, the motion of the Great Red Spot, and various characteristics of Jovian decimetre and decametre radio emission.[9,11,46] The (nearly) fixed latitude, but variable period, of the Great Red Spot[49] might be interpreted[46] as evidence of a gross magnetohydrodynamic torsional oscillation of Jupiter's internal layers involving a toroidal magnetic field of over 1000 gauss (but see reference 34). This field and the weak poloidal magnetic field of a few tens of gauss (at the visible surface) whose lines of force are not confined to the interior of the planet are produced in the lower atmosphere and/or in the metallic core of Jupiter,[9,46] if it is liquid, by magnetohydrodynamic dynamo action maintained by convection driven by gravitational energy release within the planet, involving a contraction in radius of the planet at the incredibly slow rate of 0·1 cm per year.[24,48,50-52] Thermal effects (due to ohmic heating) associated with quite moderate variations in Jupiter's internal magnetic field might give rise to detectable variations in the heat output from the planet,[46] but whether or not the observed variations are real and could be accounted for in this way requires further work. The importance of monitoring the total heat output from Jupiter and the other major planets cannot be over-emphasized.

The suggestion that the Great Red Spot is the end of a 'Taylor column'[25,27,28] in Jupiter's atmosphere[11] accounts for the observations in an unforced way without implying unlikely physical conditions in Jupiter's atmosphere and deep interior (contrary to conclusions advanced by Stone and Baker[29] whose discussion of the Taylor column hypothesis is based on an irrelevant theoretical model[9,26,27]). The nature of the associated disturbance deep in Jupiter's atmosphere and the interpretation of the long-period variations in the longitude of the Red Spot have been discussed by several writers.[9,11,24,31-33,45,46] The observation that the latitude of the Red Spot has not changed significantly places an important constraint on theories (a point which some writers have evidently overlooked). The short-period variations in the motion of the Red Spot[56] are small in amplitude and are most probably due to fluctuations in the position of the top end of the Taylor column relative to the bottom end.[26,33]

It is generally accepted that the banded appearance of Jupiter and Saturn reflects the influence of rotation on atmospheric motions, but no theoretical model that bears close physical scrutiny and comparison with the observations has yet been proposed. Wasiutynski[34] seems to have carried out the first theoretical investigation of this problem, in terms of a model characterized, among other things, by the assumption that, owing to internal heat sources, the lapse rate in Jupiter's atmosphere is superadiabatic. More recently, Stone[35] introduced a different model characterized, among other things, by the assumptions that differential solar heating is largely responsible for Jupiter's atmospheric motions, that the basic flow is mainly zonal, and that the lapse rate is subadiabatic and has a rather specific value.

Under these conditions the most unstable disturbances are axisymmetric and grow very rapidly, with typical growth times of a few rotation periods of the system. Stone[35] conjectures that Jupiter's banded structure reflects the presence of instabilities of this type after they have stopped growing,

supposing that the main properties of the fully developed disturbances resemble those of the incipient instabilities. As the theory of fully developed disturbances has not yet been worked out, it is impossible to make a useful quantitative test of Stone's suggestion, which would seem, among other things, to imply horizontal temperature variations over Jupiter's visible disc that are considerably greater than those observed[53,54] and changes in Jupiter's appearance that would be very much faster than those observed.

Gierasch and Stone[40] cite as evidence in favour of Stone's explanation of Jupiter's banded appearance their claim that the axisymmetric disturbances invoked are capable of advecting zonal momentum toward the warmer parts of the fluid and thus provide a mechanism for driving the equatorial jet (see page 271). However, there are difficulties with these arguments. They are qualitative; only the direction and not the magnitude of the rates of momentum and heat transport have been assessed. Advective processes in directions perpendicular to the rotation axis are impossible when the flow is both geostrophic and axisymmetric,[55] for the simple reason that such processes are associated with motions perpendicular to the rotation axis, which in geostrophic flow must be supported by azimuthal gradients of pressure; such motions vanish when the pressure field is axisymmetric. It follows, then, that the advective processes invoked by Gierasch and Stone[40] must be associated with departures from geostrophy. While these departures are quite large for the rapidly-growing disturbances on which these authors base their analyses, they will be very much less for fully developed quasi-steady motions unless very strong horizontal shears develop in certain regions. It might be possible to find a reasonably efficient horizontal heat transfer mechanism by invoking strong shears, but when the spherical geometry of the system is taken properly into account, the qualitative mechanism proposed by Gierasch and Stone[40] for producing and maintaining the zonal momentum of the equatorial jet would seem to be physically impossible.[26,41]

The existence of equatorial jets in the fluid layers of rapidly rotating planets seems fairly general; Jupiter and Saturn exhibit such currents, and on Earth there is the equatorial undercurrent in the oceans and the equatorial jet in the lower stratosphere. These jets, which are now the subject of a great deal of theoretical research, are not yet fully understood. If the reasonable assumption is made that the essential vorticity balance is between horizontal advection of relative vorticity and effects due to the variation of Coriolis parameter with latitude, then $(Ua/2\Omega)^{\frac{1}{2}}$ is an approximate expression for the latitudinal width of a jet of typical flow speed U relative to a rotating planet of radius a; the expression agrees satisfactorily with observations.[24,26]

The jets in all probability represent sinks for energy and angular momentum originating at higher latitudes and advected horizontally toward the equator (but see Reference 59). Considerations of the general properties of thermally driven motions in a rotating spherical shell of fluid of outer radius a_0 and total angular momentum divided by its moment of inertia equal to Ω_0 indicate that in order to account for a westerly (i.e. faster than the basic rotation) equatorial jet without appealing to sinking motions from higher levels in the atmosphere, effects due to local azimuthal pressure gradients cannot be neglected. These pressure gradients provide the only forces (in the absence of magnetohydrodynamic effects) capable of increasing the angular momentum per unit mass of an individual fluid element to a value in excess of $\Omega_0 a_0^2$.

The fluid motions invoked by Schoenberg[57] and by Gierasch and Stone[40] in their attempts to account for Jupiter's equatorial jet, without invoking either a strong source of angular momentum deep within the atmosphere (which would conflict with the observed value of the 'radio period'[42-47]) or sinking motions in the high atmosphere above the jet, are characterized by symmetry about the axis of rotation, the concomitant pressure gradients having no azimuthal component. According to the foregoing arguments, only easterly jets could be accounted for in this way; the equatorial jets of Jupiter and Saturn are westerly.

The time scales on which non-permanent planetary-scale features undergo significant changes can be incredibly long in comparison with the time required for ordinary planetary waves to disperse the kinetic energy of a typical disturbance[9] (but not in comparison with the time required for effects arising in viscous boundary layers to produce significant dissipation, $D/(\nu\Omega)^{\frac{1}{2}}$ s, assuming that the depth of the atmosphere $D \approx 10^6$m,[9,11,46] and that the effective kinematic viscosity $\nu < 10^2$m^2/s). A completely satisfactory explanation of this discrepancy has not yet been given, but the following tentative lines along which an explanation might be sought were indicated several years ago.[9]

The usual theory of ordinary planetary waves applies to the case when M (see equation (5)) is zero, whereas M is as high as 10 for Jupiter and not much less for the other major planets, all of which rotate at hypersonic speeds with respect to the speed of sound in their outer, cooler, layers. When $M \neq 0$, the dispersion relationship for ordinary planetary waves has the form

$$\omega \approx -\beta k(1-\omega^2/k^2c^2)/[k^2+l^2+(f^2-\omega^2)/c^2], \quad \ldots (6)$$

where ω denotes angular frequency, k and l the east–west and north–south wave numbers respectively, f the Coriolis parameter, β the rate of change of the Coriolis parameter with latitude, and c the speed of sound. This reduces when $M=0$ to the well-known 'Rossby-Haurwitz' formula, namely

$$\omega \approx -\beta k/(k^2+l^2). \quad \ldots (7)$$

According to Hide,[9] typical periods associated with some of the oscillatory phenomena reported by Jupiter observers,[49-56] are, at several months, comparable with those expected on the basis of equation (6), but are considerably longer than those based on equation (7). Moreover, planetary waves in hypersonically rotating fluids lose their dispersive properties, as may be shown by setting $k^2+l^2 \ll f^2/c^2$ and $\omega^2 \ll k^2c^2$ in equation (6), according to which ω/k, the phase velocity, is then the same as the group velocity, $\partial\omega/\partial k$. It was in terms of this result that Hide proposed an explanation of the great duration of Jupiter's South Tropical Disturbance, which first arose in 1901 and gave way in 1939 to three prominent white spots[49] which can be seen at the present day.

Because Jupiter rotates very rapidly, atmospheric motions at the level of the visible surface of dense cloud should be highly correlated with the motions in the lower reaches of the atmosphere.[11,27] Therefore, the hypothesis that the latter motions play a significant role in the production of Jupiter's magnetic field (see page 272) can be tested by determining details of the configuration of the magnetic field and ascertaining the extent to which they are correlated with the appearance of the visible surface and with temperature variations at that level, an experiment which should be feasible as part of the projected Grand Tour programme.[58]

The central theoretical difficulty in all dynamical studies of motions in planetary atmospheres is that of understanding interactions between motions on different length and time scales. Current deficiencies in our knowledge of the scales of motion present in the atmospheres of the major planets (including the details of certain conspicuous features such as the edges of the strong equatorial currents on Jupiter and Saturn and Jupiter's Great Red Spot) will not be remedied until better photographs and thermal maps have been obtained over a long period of time. Owing to the great distance between the Earth and the giant planets, there is no observational evidence from which the scales of motion on Neptune can be deduced and indications of planetary-scale banded structure are vague in the case of Uranus, but are rather better for Saturn. There is (weak) evidence of a strong equatorial jet on Saturn (400 m/s, four times faster than Jupiter's equatorial jet), but its latitudinal width ($\approx 15°$ for Jupiter) has not yet been resolved; simple theory indicates that this width should be $\approx 30°$, and future observations will doubtless indicate whether or not this is so.

Amongst the programmes of fundamental research that will be essential if the best possible use is to be made of the data expected from the International Planetary Patrol[1] and the forthcoming Grand Tour[58] will be laboratory, mathematical, and numerical studies of the hydrodynamics and magnetohydrodynamics of rapidly rotating fluids (a strategy for which has been outlined elsewhere[26]). Interest in these difficult and still poorly developed areas of classical physics has resulted partially from observational work in dynamical meteorology, oceanography, geomagnetism and astrophysics (e.g. pulsars); and many examples of successful interactions between observational and theoretical work can be cited. Fluids that rotate at speeds not much greater than the speed of sound within them (e.g. atmospheres of Earth and Mars) differ fundamentally in their behaviour from fluids that rotate hypersonically, for example atmospheres of Jupiter and the other major planets, and it is therefore worth noting that the study of hypersonically rotating fluids remains an almost untouched area of fluid dynamics.

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TEMPERATURE DIFFERENCES BETWEEN A GROUND-LEVEL SITE AND A ROOF SITE AT NEWCASTLE UPON TYNE

By G. A. JONES

Summary. Extreme temperatures over the period June 1967 to May 1970 at a roof site at Newcastle Weather Centre were compared with those at a ground-level site at the University about 900 yards distant. The maxima at the two sites were within ± 1·5 degF on 88·2 per cent of days and showed some seasonal variation. The minima were within ± 1·5 degF on 82·9 per cent of days. The range of differences in minima was greater than that for maxima. With clear skies at night and light variable or calm winds on the Weather Centre roof the University minima are likely to be lower than the roof values. With clear skies at night and light to moderate south-west to north-west winds on the Weather Centre roof the University minima may be higher than roof values. There was a closer agreement in the extreme temperatures at the Newcastle sites than for corresponding comparisons at London and Southampton.

Introduction. Three years' temperature observations have now been recorded at the Newcastle Weather Centre roof site and these have been compared with readings at the University ground-level site, in much the same way as was done for temperatures at London[1] and Southampton.[2]

The sites. The two Newcastle sites are close to the city centre and are 900 yards* apart. At both sites the thermometers are contained in standard thermometer screens. Readings are in Celsius at the Weather Centre and in Fahrenheit at the University. The Celsius readings have been converted to Fahrenheit for convenience in comparing readings with previous work. The main results are quoted in Celsius elsewhere in the text.

The Weather Centre screen is anchored to a flat asphalt roof, 100 feet (≈30 m) above street level. The roof in the immediate vicinity measures 24 feet by 15 feet and is surrounded by an iron railing, 3 feet 6 inches high. The roof, although not the highest in the city, overlooks many buildings and the screen is well exposed to the elements.

The University site is not ideally exposed but on the other hand is representative of a sort of garden environment in a tree-lined city square.

* Distances and heights are given in traditional British units. Conversion factors to metric units are : 10 yd ≈ 9·1 m; 1 ft = 0·3048 m; 1 kt ≈ 0·5 m/s.

The site is about 50 yards square surrounded by trees and enclosed by 6-foot wooden palings. The trees are deciduous, the majority being sycamores, and are about 40 feet high. The screen is near the centre of the enclosure and next to a disused concrete tennis court. The remainder of the enclosure is taken up with long grasses and scattered bushes. Around the whole square there is a road, beyond which on three sides are terraced houses. To the north-west is a large area of open ground — the Town Moor.

Maximum temperatures. The differences between the maximum temperatures (09–09 GMT), at the two Newcastle sites are shown in Table I.

TABLE I—MONTHLY AVERAGE DIFFERENCES IN MAXIMUM TEMPERATURES READ AT THE UNIVERSITY AND WEATHER CENTRE, JUNE 1967 TO MAY 1970

	Difference in maximum temperatures (University values minus Weather Centre values)		
	1967–68	1968–69	1969–70
	degrees Fahrenheit		
June	+1·3	+1·1	+1·2
July	+1·0	+0·6	+0·5
August	+0·5	+0·6	+0·2
September	+0·5	+0·1	−0·3
October	0·0	−0·2	−0·3
November	−0·2	−0·3	−0·3
December	−0·1	−0·4	−0·5
January	−0·4	−0·5	−0·3
February	−0·1	−0·1	+0·1
March	+0·7	0·0	+0·5
April	+0·9	+0·4	+0·9
May	+0·8	+0·4	+0·7

The greatest differences were mainly in the spring and summer, when the University maximum temperatures were on the average up to 1·3 degF higher than the Weather Centre readings. The autumn and winter differences showed a tendency for the University maxima to be a little lower than the Weather Centre values. March 1969 was cold and more like a winter month, so that in the spring of 1969 the difference did not become positive until April.

Table II summarizes the daily differences between the maxima at the two sites, the readings having been rounded off to the nearest whole degree Fahrenheit.

TABLE II—NUMBER OF DAYS (09–09 GMT) WITH SPECIFIC MAXIMUM TEMPERATURE DIFFERENCES, ROUNDED TO NEAREST WHOLE DEGREE FAHRENHEIT, AT THE UNIVERSITY AND WEATHER CENTRE, JUNE 1967 TO MAY 1970

Difference* *degF*	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Total	
	number of days													*per cent*
−3				1			1	1					3	0·3
−2			2	2	1	3	1	7	2	1		2	21	1·9
−1	2	7	7	22	33	26	25	25	17	7	7	12	190	17·3
0	11	27	44	35	43	52	41	55	46	49	28	23	454	41·4
+1	49	43	32	26	13	7	19	4	19	33	36	42	323	29·5
+2	21	13	6	4	1	2	6		1	3	14	12	83	7·6
+3	5	2	2		2			1			5	2	19	1·7
+4	2	1											3	0·3

* University values minus Weather Centre values.

Table II reveals that the maxima at the two sites were within ±0·5 degF on 41·4 per cent of the days and within ±1·5 degF on 88·2 per cent of the days.

Maxima differences of more than 1·5 degF occurred on 129 days and 88 of these, occurring in the spring and summer, gave higher temperatures at the University site

Minimum temperatures. Similar comparisons of minimum temperatures are set out in Tables III and IV.

TABLE III—MONTHLY AVERAGE DIFFERENCES IN MINIMUM TEMPERATURES READ AT THE UNIVERSITY AND WEATHER CENTRE, JUNE 1967 TO MAY 1970

	Difference in minimum temperatures (University values minus Weather Centre values)		
	1967–68	1968–69	1969–70
	degrees Fahrenheit		
June	0·0	+0·1	+0·2
July	+0·6	−0·3	+0·4
August	+0·2	0·0	−0·1
September	+0·5	−0·2	−0·2
October	+0·5	−0·1	+0·2
November	+0·1	−0·1	−0·3
December	0·0	−0·4	−0·2
January	+0·1	0·0	+0·2
February	−0·2	+0·2	+0·1
March	+0·3	−0·2	+0·1
April	−0·3	−0·4	+0·3
May	−0·8	−0·2	+0·2

The differences in minima were on the average well within ±1·0 degF, and unlike the differences in maxima, there were no seasonal variations.

TABLE IV—NUMBER OF DAYS (09–09 GMT) WITH SPECIFIC MINIMUM TEMPERATURE DIFFERENCES, ROUNDED TO NEAREST WHOLE DEGREE FAHRENHEIT, AT THE UNIVERSITY AND WEATHER CENTRE, JUNE 1967 TO MAY 1970

Difference* *degF*	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Total	
	number of days													*per cent*
−6						1						1	2	0·2
−5					1		1	1	1	1	2	2	9	0·8
−4	2	1	1			3			1	1	2	2	13	1·3
−3	3	2	1	5	4		3	3	3	6	7	4	41	3·7
−2	4	4	5	6	2	4	9	1	7	3	2	6	53	4·8
−1	10	10	18	14	15	13	14	13	9	8	16	9	149	13·6
0	37	30	33	27	27	45	45	42	28	37	24	30	405	36·9
+1	28	39	30	30	38	19	15	30	32	30	29	35	355	32·4
+2	5	4	5	8	5	5	6	2	3	5	7	3	58	5·3
+3	1	2						1	1		1	1	7	0·6
+4		1								2			3	0·3
+5					1								1	0·1

* University values minus Weather Centre values.

On 36·9 per cent of the days the differences in minima were within ±0·5 degF and on 82·9 per cent of the days the differences were within ±1·5 degF. The range in minima differences was greater than the range of differences in maxima. There were 4 days when the minimum at the University was more than 3·5 degF higher than at the Weather Centre and 24 days when it was more than 3·5 degF lower.

Comparison with roof sites at London and Southampton. There was a closer agreement in the extreme temperatures at the two Newcastle sites than for similar comparisons at London and Southampton. On 41·4 per cent of the days the daily differences in maxima between the two Newcastle sites lay between ±0·5 degF compared with London 25·2 per cent and Southampton 26·5 per cent. With regard to the minima, the comparable percentages for the differences between ±0·5 degF are, Newcastle 36·9, London 13·7 and Southampton 30·6 per cent.

At Newcastle the peak number of days occurred when the daily differences of maximum and minimum temperatures were 0 degF. However, at London and Southampton the peaks occurred at roof maxima about 1 degF below the values at ground level and at roof minima about 1 degF above the values at ground level.[1,2]

The height differences between the roof and ground-level sites at Southampton, Newcastle and London are 33 feet, 101 feet and 122 feet respectively, and it seems that up to 100 feet or so over cities there is no universal relationship between temperature and height. Other factors such as size and distribution of buildings, their thermal capacities, seasonal changes in vegetation in city squares, local topography and so on must be playing an important role in the heat budgets, so that each city has its own peculiar lapse rates.

Temperature extremes between the two Newcastle sites. Continuous temperature readings are available from the Weather Centre roof but extremes are read only once a day at the University, and although on a climatological basis the 24-hour extreme temperatures at roof level are close to those at ground level, there is a need for the forecaster to be aware of the odd occasions when large temperature differences may occur, especially in the minima.

The Weather Centre hourly temperatures were examined on the 11 days when the University minimum readings were lower by more than 4·4 degF and on the 11 days when they were higher by more than 2·4 degF, in order to find the probable time of the minima. A note was then made of the cloud and wind observed on the Weather Centre roof for the preceding 12 hours, together with the geostrophic wind at the main synoptic hours. The 09 GMT temperatures at the two sites were also examined.

It was found that 17 of the 22 cases were associated with less than 4/8 mean amount of low cloud. The other 5 cases had a mean of 5/8–7/8 but with breaks to less than 4/8 at times. The cases when the University site was colder were associated with light and variable breezes at roof level and sometimes calm conditions. The geostrophic winds were south-easterly or else were westerlies that became light and variable. However, it would appear that the lower minima at the University were only a temporary feature, since by 09 GMT, except for one case, the University temperatures had recovered and slightly overtaken the Weather Centre values.

In contrast, on the days when the University reported higher minima the light to moderate roof-level wind speed continued throughout the night with directions from between south-west and north-west. The geostrophic winds were from between south-west and north-north-east and varied between 15 and 44 kt. The 09 GMT readings gave higher University values on all 11 days.

From these extreme cases it appears that on some clear nights, lapse rates to at least 100 feet over Newcastle are related to the speed and direction of the wind and resulting turbulence, stable conditions being associated with calm or light and variable breezes and unstable conditions with light to moderate breezes from between south-west and north-west. This latter unstable state could be a decisive factor in preventing (or clearing) radiation fog.

It may be that on many other occasions of clear skies the wind is also an important factor but to a lesser degree, i.e. all those cases when the temperature differences between roof and ground level were less than the 2·4 degF and 4·4 degF extremes. The following tentative rules are suggested concerning Newcastle minima :

Rule 1. With clear skies at night and light and variable or calm winds on the Weather Centre roof, the University minima are likely to be lower than the roof values (6 degF (3·3 degC) lower is possible but rare) but with University temperatures recovering during daylight.

Rule 2. With clear skies at night and a persistent light to moderate south-west to north-west wind on the Weather Centre roof, University minima may be higher than roof values (3 degF (1·7 degC) higher is possible but rare).

Conclusions. The temperature differences at the two Newcastle sites over a period of three years were compared and the following results obtained :

(i) Maximum temperatures differed on the average for the month by small amounts and the differences showed a seasonal variation.

(ii) On a day-to-day basis 88·2 per cent of the roof maxima and 82·9 per cent of the minima were within ±1·5 degF (±0·8 degC) of the University ground-level values, but the range of differences in the minima was greater than that in the maxima.

(iii) Most of the differences greater than 1·5 degF (0·8 degC) gave higher maxima at the University in the spring and summer.

(iv) The differences in extreme temperatures between roof and ground level were in closer agreement than for similar comparisons at London and Southampton.

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A COMPARISON OF METHODS OF FORECASTING NIGHT COOLING AT SCREEN LEVEL

By W. E. SAUNDERS

Summary. Recent tests of night cooling forecasting methods are reviewed. It is shown that there is considerable spatial variation of accuracy in the use of the Saunders method, and that at present this method appears to be least accurate at stations bordering on the Fens.

In recent years, the night cooling forecasting procedure suggested by the author,[1] and afterwards adapted for widespread use by Barthram[2] and Tinney and Menmuir,[3] has been tested at a number of stations and compared with methods due to McKenzie[4] and Craddock and Pritchard.[5]

It has been thought worth while to bring these test results together to see what conclusions might be reached, and this has been done in Table I.

In Table I, the results included are those of actual forecasts made before the event, and so incorporate errors in forecasting the wind speed and cloud amount, as well as those inherent in the methods.

The tests have been numbered in order of publication for ease of reference. In order to simplify comparison, the values of root-mean-square error or

TABLE I—RECENT TESTS OF NIGHT COOLING METHODS

Test No.	Authors	Stations tested	Forecasting method: Saunders Standard deviation	Saunders Root-mean-square error	McKenzie Root-mean-square error	Craddock and Pritchard Root-mean-square error
				degrees Celsius		
1.	Gordon and Virgo[6]	Mildenhall	—	2·16	2·09	—
2.	Steele, Stroud and Virgo[7]	Cottesmore	1·24	—	—	—
		Lindholme	1·39	—	—	—
		Finningley	1·45	—	—	—
		Scampton	1·64	—	—	—
		Waddington	1·66	—	—	—
		Wittering	1·72	—	—	—
		Bassingbourn	2·00	—	—	—
		Mildenhall	2·06	—	—	—
		Marham	2·24	—	—	—
		Wyton	2·40	—	—	—
3.	Gordon, Perry and Virgo[8]	Mildenhall	—	—	2·14	2·30
4.	Abbott[9]	South-west England	—	1·90	—	—
5.	Ritchie[10]	Wyton	—	2·60	2·60	—

standard deviation given separately for different seasons or types of occasion in the test reports have been meaned in Table I. Generally, in this work, the differences between root-mean-square error and standard deviation are very small.

The list of standard deviations included in Test 2 is the mean of the standard deviations for clear and cloudy nights for summer and winter periods given in Tables I and II of Reference 7. Stations have been arranged in ascending order of standard deviation. The outstanding feature of this table is the wide variation between the results for the station where the highest accuracy was obtained (Cottesmore) and the station whose results were least satisfactory (Wyton).

The authors of Test 3, after referring back to Test 1, concluded that there is very little to choose between any of the three methods in practice. The author of Test 5 found it surprising, in view of the speed and simplicity of the McKenzie method, that tests should show little to choose between the methods.

However, reference to the results of Test 2, as presented in Table I, shows that one aspect which requires to be emphasized is that Tests 1, 3 and 5 all refer to two stations, Mildenhall and Wyton. These stations are at the lower end of the spectrum, where for some reason the Saunders method is decidedly less accurate than at many other stations. It may of course be that all three methods work equally well at all stations, but this is not demonstrated or implied in any of the published tests.

In Test 4, the root-mean-square error included is the mean of the root-mean-square errors for Day 1, taken from Table II of Reference 9. This is of special interest, as the technique has been used here for forecasting a mean minimum temperature for four stations. Also, these were operational forecasts issued before 09 clock time, so that maximum temperatures and dew-points at the time of maximum temperature used in the forecasts would

themselves have had to be forecast, instead of actual values being used. Hence the root-mean-square error compares very well indeed with the others reported.

Reverting to Test 2, the common feature between stations where the lowest accuracy is obtained using the Saunders method appears to be their position near the edge of the Fens, as shown in Figure 1. This is certainly the case with Mildenhall and Wyton, the stations used in Tests 1, 3 and 5. Possibly, reduced accuracy at these stations might be due to a significant number of occasions when evening or night drift from the Fens renders the starting data non-representative for the station. It might be necessary to deal with these cases in the way that coastal stations with on-shore winds are dealt with. Detailed analysis of forecast errors at one of these stations might perhaps reveal what could be done to improve the results.

FIGURE 1—SPATIAL DISTRIBUTION OF STANDARD DEVIATION, DEGREES CELSIUS, IN TEST OF SAUNDERS METHOD BY STEELE, STROUD AND VIRGO

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OBITUARY

It is with regret that we have to announce the death of Mr R. E. Barden, Senior Scientific Assistant, Gatwick, on 26 May 1971.

REVIEW

Introduction to meteorological optics, by R. A. R. Tricker. 215 mm×175 mm, pp. 285, *illus.*, Mills and Boon Ltd, 17–19 Foley Street, London, W1A 1DR, 1970. Price: £4·20.

Strange optical phenomena in the sky have been a source of fascination to the mind of man from the earliest times, yet even today there are some phenomena whose origin is not fully understood. The fact is that although, as Dr Tricker points out in the preface to his book, special observatories for the study of meteorological optics were set up on the tops of mountains in the last century, interest has since been diverted to other fields of study. Nevertheless, the need for both careful observation and adequate theoretical exploration of optical phenomena occurring in nature still remains.

In *Introduction to meteorological optics*, Dr Tricker endeavours to fill a gap in the literature on this subject. He not only describes the principal phenomena which have been observed, but also seeks to show how they arise and to give the relevant mathematical analysis. In doing so, he assumes that his readers have a good knowledge of algebra and elementary trigonometry, together with some knowledge of differential calculus. This seems a good level to start from, since it is sufficiently advanced to allow the author to discuss quite complicated problems, but sufficiently general to allow most readers with a scientific background to follow his argument.

The text itself is interspersed with a number of thought-provoking comments, especially on the need for careful observation. For instance, Tricker says, 'The rainbow furnishes a good example of how observation is guided by theory — and not always to the advantage of the former. The Cartesian theory proved so successful . . . . that the fact that it failed to indicate many other accompanying features' (e.g. the variable apparent width and brightness of the bow and variations in the intensity of the colours) 'was overlooked.' Again, in the chapter on the glory, Tricker remarks that some of the early drawings 'cast a very candid light on the power of man's observation.' He then reproduces a drawing made of the glory by a Spanish Captain Ulloa who observed the phenomenon from the top of a mountain in Peru in 1735.

In this drawing the glory is represented as if the observer had seen it around the shadow of a companion's head, although in fact one can only ever see a glory around one's own head!

There are, however, several aspects of this book which are rather disappointing. For example, the colour plates used to illustrate the rainbow and the glory are rather insipid and many of the other phenomena are not illustrated at all. There is a lack of sub-headings which makes the text unnecessarily difficult to follow, especially in the long chapter on ice-particle haloes. There is also a chapter on the Mie theory for the scattering of light by small droplets which is rather out of place in this book since the theory is probably too difficult for the general reader, whilst the specialist would be inclined to look elsewhere for a treatment of this particular topic.

Despite these criticisms, Tricker's treatment is for the most part clear and convincing. It is perhaps only a little unfortunate that, whilst he is quick to point out the short-comings of earlier discussions of the heiligenschein, he fails to give credit to Minnaert who put forward the same explanation in his book on *Light and colour in the open air*.

The weakest part of the book is probably the section where Dr Tricker propounds a new theory for some of the unusual features of ice haloes. Here he strongly criticizes the theories given by previous workers and suggests that the explanation lies in the existence of ice crystals in the form of elongated hexagons which spin about their longest horizontal axes as they fall through the air. I am, however, not at all sure that Tricker's strictures of early theories are entirely justified. Nor does it seem likely that spinning crystals of the type he proposes exist in significant numbers in natural clouds and, even if they do, it is not clear how they differ from randomly oriented platelets.

Nevertheless, this book can be welcomed as it undoubtedly goes part way to filling a gap in the literature and should do much to encourage careful observation and to revive interest in this most intriguing branch of meteorology.

J. T. BARTLETT

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